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MAY 80 R D HOLDEN, A A MOORE, K G IKELS
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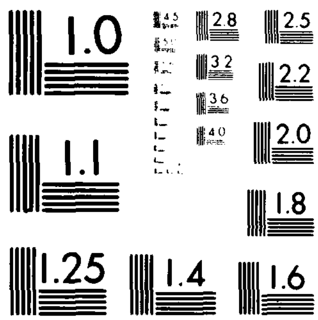

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The Navy/Air Force Oxygen Generating System (NAOGS) program is a joint effort between the Air Force and the Naval Air Development Center to develop a 2-man onboard oxygen generator for tactical aircraft. One of the proposed systems is based upon reversible sorption of oxygen from aircraft engine bleed air using fluomine, a cobalt chelate. The NAOGS fluomine system was manufactured by Garrett/AiResearch Division, Torrance, California. The USAF School of Aerospace Medicine performed man-rating of the NAOGS-fluomine unit prior to flight test by the U.S. Navy. The experimental protocol at USAFSAM consisted of both unmanned

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and manned testing, during which the product oxygen was monitored for quantity, purity, and trace contaminant content. Man-rating consisted of actual flight simulations with 2 test subjects at four different altitudes for periods up to 2 hours while breathing the product oxygen. The NAOGS, for the most part, performed adequately during both manned and unmanned testing. The exceptions were a lower than specification oxygen production rate and a short-term drop in oxygen purity during each bed switching cycle. These shortcomings are discussed in the context of the forthcoming flight test program.

MAN-RATING OF THE NAVY/AIR FORCE OXYGEN GENERATING SYSTEM (NAOGS)

INTRODUCTION

The Navy/Air Force Oxygen Generating System (NAOGS) program is a joint effort between the Air Force Life Support System Program Office (ASD/AEL) and the Naval Air Development Center (NADC) to develop a 2-man on-board oxygen generating (OBOG) unit for tactical aircraft. Although several OBOG concepts were originally proposed, only two systems were developed to the prototype stage for man-rating and flight test. These included systems based on (a) molecular sieve separation of air, and (b) reversible sorption of oxygen using a cobalt chelate, fluomine. Per agreement with the Life Support System Program Office, the USAF School of Aerospace Medicine (USAFSAM) conducted man-rating of each OBOG system using human test subjects in simulated flight profiles. The molecular sieve unit was man-rated by USAFSAM in late 1977 (1, 2). This report describes test methods and results from USAFSAM man-rating of the 2-man NAOGS fluomine unit.

The NAOGS unit and test stand were received at Brooks AFB, Texas in late May and subsequently man-rated during June and early July 1978. The hardware was forwarded to NADC in late July 1978 for installation on the U.S. Navy EA-6B aircraft for flight testing at the Naval Air Test Center, Patuxent River, Maryland.

METHODS

Description of the System

The NAOGS fluomine system was manufactured by Garrett/AiResearch Division, Torrance, California, as P/N 133982-1-1. The system, shown pictorially in Figure 1 and schematically in Figure 2, was composed of two fluomine beds (configured as plate-fin heat exchangers), a 3-stage compressor, and associated valves and fittings. Process air (from an external instrument air supply) was fed to each bed sequentially by an inlet selector valve. During the loading half-cycle, fluomine [bis(3-fluorosalicylaldehyde) ethylenediimine cobalt-II] absorbed oxygen from the process air. The nitrogen-rich exhaust was vented to ambient. During the desorption half-cycle, the bed was isolated from the process air and heated to release the oxygen, which was pumped

1. Miller, R. L., et al. Molecular sieve generation of aviator's oxygen: Breathing gas composition as a function of flow, inlet pressure, and cabin altitude. SAM-TR-77-40, Dec 1977.

2. Stork, R. L., et al. Human compatibility testing of a 2-man molecular sieve oxygen generator. SAM-TR-78-18, May 1978.

out by a 3-stage compressor to a 1-liter storage accumulator. The first portion of the product gas was discarded to remove residual (interstitial) nitrogen and other impurities. The total cycle time for each bed was approximately 3 1/2 minutes.

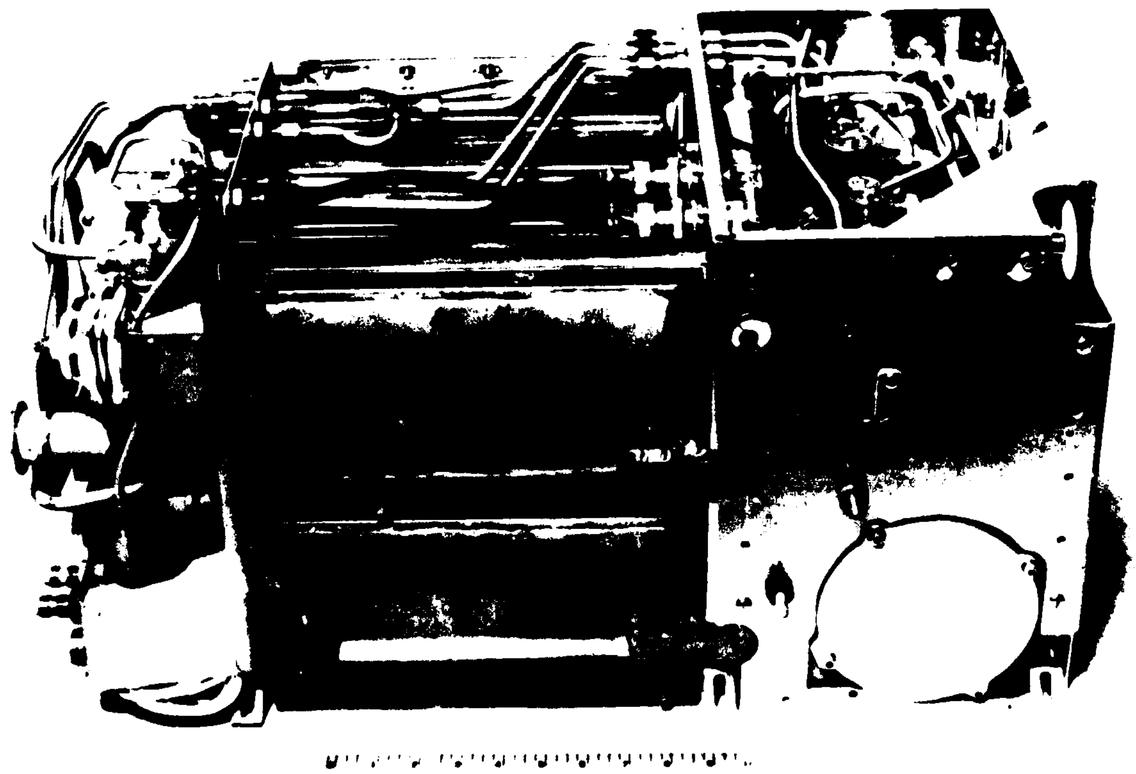

Figure 1. Navy/Air Force 2-man Fluomine Oxygen Generating System (NAOGS).

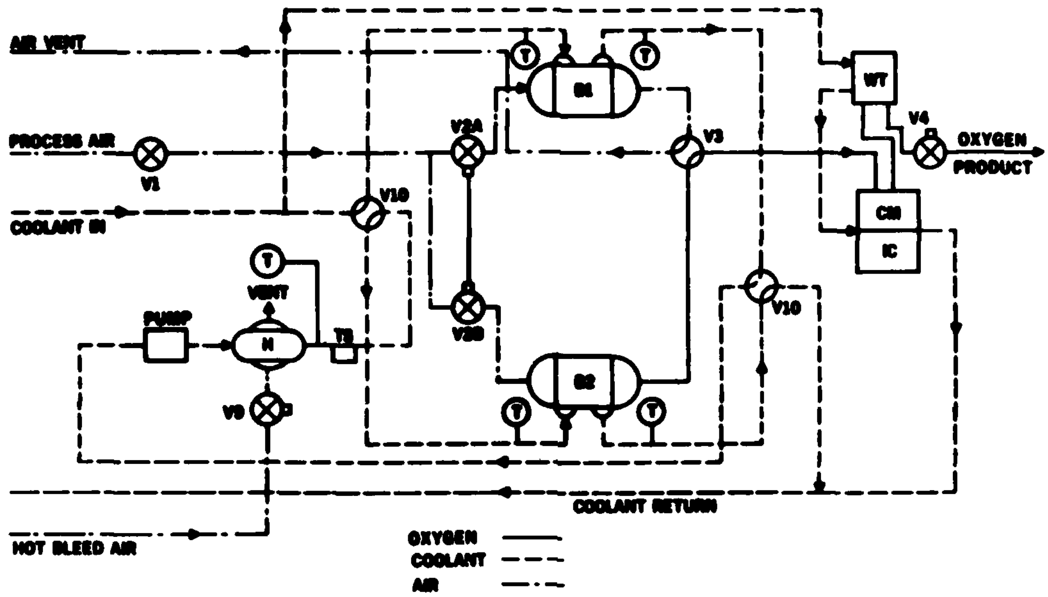

Figure 2. Flow schematic of 2-man Fluomine Oxygen Generating System.

Key

Item	Part name
B1	Sorbent bed
B2	Sorbent bed
CM	Compressor
H	Heat exchanger
IC	Intercooler
Pump	Coolant pump
T	Temp measurement boss
TS	Temperature sensor
V1	Pressure regulating valve
V2	Air sequencing valve
V3	Oxygen sequencing valve
V4	Nitrogen purge valve
V9	Modulating and shutoff valve
V10	Coolant sequencing valve
WT	Water trap

Man-Rating Test Setup

The test setup for the man-rating procedure is shown schematically in Figure 3. The product oxygen from the NAOGS was continuously monitored for quantity, purity, and trace contaminant content. An oxygen testing manifold was constructed from large diameter copper tubing to accommodate the necessary test probes and assure no restriction of flow. The manifold was fitted between the regulated oxygen supply of the NAOGS and the supply line leading to the research chamber housing the 2-subject test crew. An in-line bleed valve was installed to vent the product oxygen to ambient during the preliminary unmanned testing. The test manifold contained monitoring equipment (mass spectrometer) to check for the oxygen, nitrogen, carbon dioxide, and argon content of the product oxygen as well as a probe to measure dew point (Panametrics Model 2000) and a mass flowmeter (Technology Inc. Model LFC-6) to measure the quantity of gas produced. The mass spectrometer (Perkin-Elmer Model MGA-1100) used to monitor oxygen purity required a sample volume of 60 ml/min, which was added to the total product gas recorded by the mass flowmeter. The balance of the continuous monitoring instrumentation was in-line and nondestructive. Occasional grab samples were taken for carbon monoxide analysis by infrared (Wilkes Model Miran) and for trace hydrocarbon analysis by gas chromatography-mass spectrometry (Dupont Model 21-491). The grab samples were scheduled for times when delivered oxygen volumes were not being measured. A particulate filter consisting of a 0.45-μm pore filter paper on wire mesh was installed in the oxygen line to check for possible cobalt and fluorocarbon contamination during oxygen production.

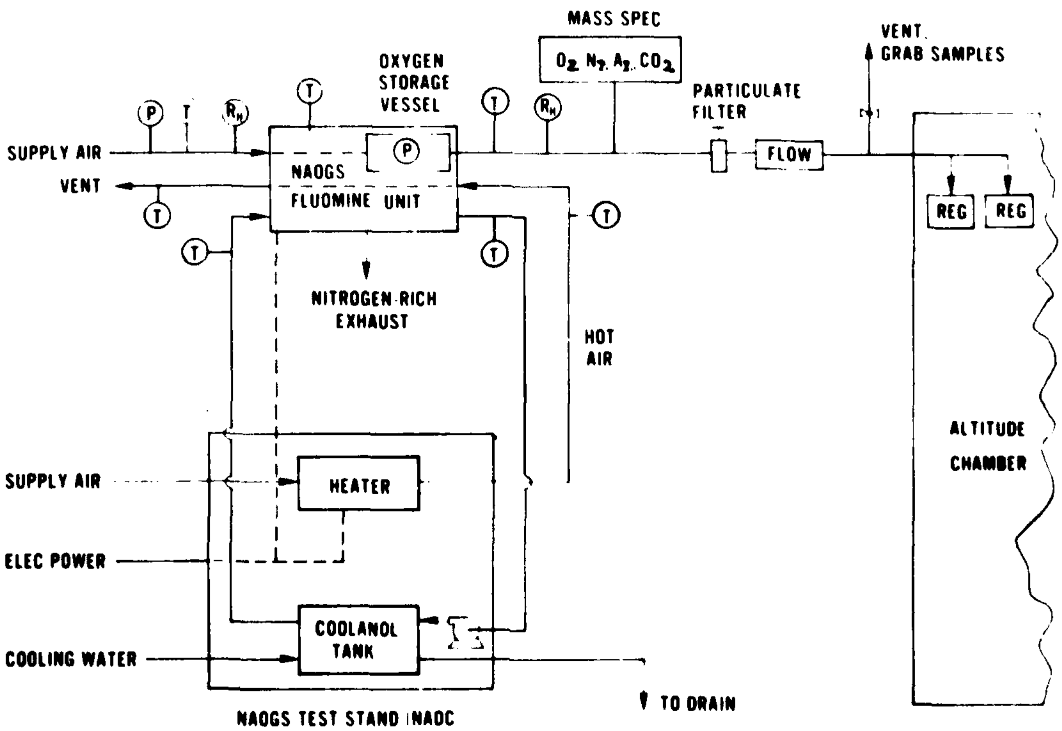

Figure 3. Schematic of test setup.

RESULTS

Simulated Tests

Oxygen Quantity--Table 1 compares several rates of steady flow with the duration time for emptying the NAOGS system when starting with a full oxygen storage tank. The depletion end point used was 70 psig which was the minimum pressure necessary to drive the Bendix oxygen regulators. Set/static flows ranging from 13 to 52 liters/minute (lpm) were withdrawn from the NAOGS and monitored for purity, contamination, and duration. The 1800-psig oxygen storage tank of 1000-cm^3 capacity furnished about 120 liters ambient temperature and pressure dry (ATPD) of gas to provide for low oxygen production during bed cycling, as well as for startup and instantaneous peak demand. The NAOGS was designed to provide oxygen at a rate of 4.6 lb/hour (26 lpm at sea level, 21°C). The measured production rate for oxygen fell approximately 20% below the specification.

Oxygen Quality--On the average, the oxygen content of the NAOGS-delivered product gas remained above the 98.5% minimum specified level. However, during a 30-second segment of each 3 1/2-minute sorbent bed cycle, the oxygen concentration dropped to a value in the range from 70% to 90% (Fig. 4). All tests exhibited this cyclical drop in oxygen percentage every 3 1/2 minutes, with the exact amount of variability appearing to be a function of the outlet flow from the NAOGS. The amount of oxygen percentage drop and nitrogen increase appeared as mirror images during each bed cycle, which probably reflected a trace amount of air leakage during the valve changeover cycle.

TABLE 1. NAOGS OXYGEN DURATION AT STEADY FLOW

Flow rate (lpm)	Approximate duration
13	Indefinite
20	3-4 hours
21	1 hour
22	45 minutes
26	20 minutes
39	7 1/2 minutes
52	4 minutes

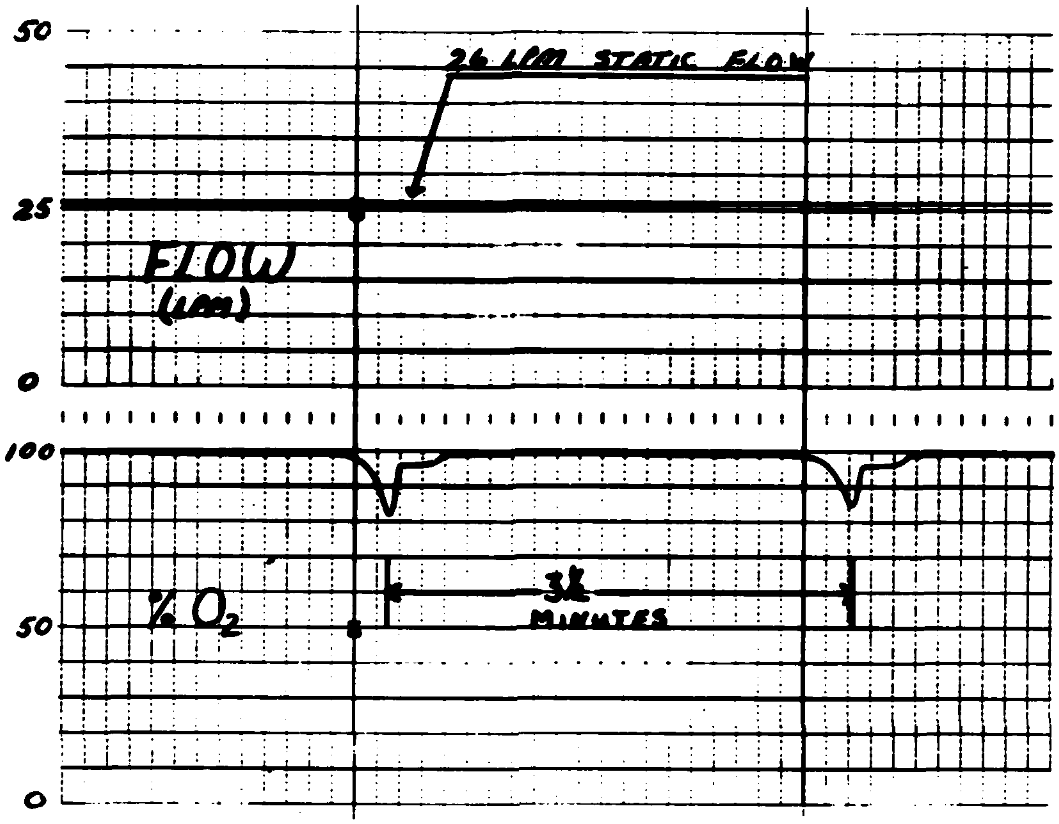

Figure 4. Product flow rate and oxygen purity as a function of time during NAOGS cycle changeover.

CO, CO_2, Dewpoint--Throughout the NAOGS test program, the carbon monoxide (CO) and carbon dioxide (CO_2) concentration in the product oxygen ranged from 20-35 and 300-700 parts per million (ppm) respectively. The average values were 28 and 585 ppm for CO and CO_2, respectively. Variations appeared to be a function of when the sample was taken. Day-to-day values fluctuated around these means and apparently were affected by how long the NAOGS had been running and the pressure in the oxygen storage tank at the time of sampling. The NAOGS, with only about 50-60 hours of operation, had not been run long enough to determine if an increase in the CO and CO_2 levels occurred with fluomine degradation. The dewpoint of the product oxygen ranged from -10°C to +10°C, primarily due to variation in the dryness of the bleed air supply.

Temperature--In all tests, the product oxygen remained at essentially room temperature, 23-25°C. The heated air supply (used to heat the Coolanol) ranged from 190-220°C and revolved around a set point of 204°C during each sorbent bed cycle. Raising the heating air temperature set point to 232°C did not measurably improve the oxygen production rate. The cold Coolanol inlet and outlet temperature extremes ranged from about 35 to 65°C, respectively.

Trace Contaminants--The results of the grab sample analysis of NAOGS produced oxygen by TENAX-GC Sorption Tube and Gas Chromatograph-Mass Spectrometer(GC-MS)-Data System indicated no significant concentration of organic material (Table 2). A high concentration of chloroform was found in one sample obtained from the first oxygen produced after the NAOGS was idle. This may have been an off-gas accumulation which rapidly dropped during operation as shown in sample 2.

TABLE 2. GC-MS ANALYSIS OF GRAB SAMPLES OF NAOGS-PRODUCED OXYGEN

Compound	Sample #1 μg/m^3	Sample #2 μg/m^3
Olefin		
1-Butene	1.6	1.4
Aromatic		
Benzene	1.9	2.4
Aldehyde		
Acetaldehyde	3.5	5.5
Alcohols		
Isopropyl alcohol	1.9	2.5
Nitrogen-containing		
Methyl isocyanide	1.7	2.4
Halogen-containing		
Dichloromethane	0.9	1.1
Chloroform	57.3	1.8
Unknown	5.5	8.1

The in-line Gelman particulate filter showed a trace of cobalt (1.5 μg/52 hours of operation). This may be considered insignificant. Daily "sniff" tests of the output oxygen showed no noticeable odors or unusual smells emanating from the NAOGS.

Man-Rating

Man-rating was accomplished by 2 test subjects breathing from the NAOGS unit during a simulated flight test profile. The man-rating flight altitude-time schedule is shown in Figure 5. The total test time was 2 hours and the maximum cabin altitude was 18,300 ft (5,580 m). Each subject was provided NAOGS oxygen via a harness-mounted regulator (USAF CRU-66/A) operated in the 100% mode, and a standard oxygen mask (MBU-5/P). Each man-rating test was initiated with a full oxygen storage tank (1500 psig minimum) and with power

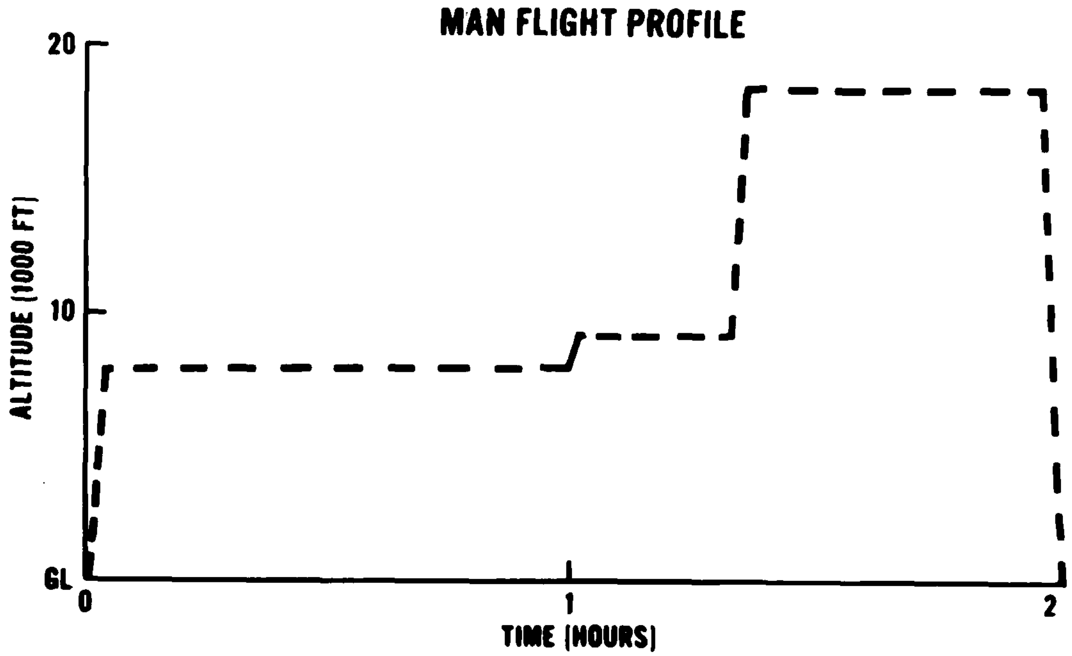

Figure 5. Altitude-time simulated flight profile for man rating of 2-man fluomine oxygen generator.

on to the NAOGS unit. Because of internal pressure switches, the NAOGS compressor was not always generating as testing was begun. As pressure built up, the compressor cycled off at approximately 1750 psig and cycled on when the pressure decayed to about 1400 psig.

During flight 1 the oxygen storage tank pressure was initially 1620 psig and dropped to 1160 psig at the lowest point, which occurred 6 minutes into the flight profile. From that low pressure point, the NAOGS produced sufficient oxygen to maintain the 2 crewmen and slowly replenish the oxygen storage tank pressure. Refilling took about 30 minutes, and a pressure of greater than 1400 psig was maintained for the remainder of the flight. As indicated earlier, the oxygen concentration cycled for a short period (30 sec) during each bed changeover. The low point in flight 1 was an oxygen concentration of 78%; however, the average oxygen concentration for the run remained above 98%. The minute volume for the 2 subjects averaged 15-18 lpm for the 8,000 ft (2,439 m) portion of the flight.

At the start of flight 2 the oxygen storage tank pressure was 1600 psig and dropped to a low value of 600 psig after 16-18 minutes. The storage tank did not completely refill until 1.5 hours into the test at a flight level of 18,300 ft (5,580 m). Except for the low segments of each cycle, the oxygen concentration was maintained at greater than 98%. The lowest oxygen concentration noted for any flight 2 sorbent bed cycle was 75%. The minute volumes for the 1-hour period at 8,000 ft (2,439 m) averaged between 20-25 lpm with a few of the instantaneous peaks reaching 0.67 liters/sec (40 lpm). Table 3 summarizes the average minute volumes observed for the 2 crewmembers in each test flight.

TABLE 3. MINUTE VOLUMES FOR TWO TEST SUBJECTS IN SIMULATED TEST FLIGHT

Altitude (ft)	Approximate minute volume (lpm, ATPD)	
	Flight 1	Flight 2
8,000 (2,439 m)	15-18	20-25
9,100 (2,774 m)	20-22	15-20
18,300 (5,580 m)	10-15	10-15

DISCUSSION

Man-rating of the NAOGS surfaced two possible problem areas. One was the lowered oxygen percentage for about 30 seconds of each 3 1/2-minute cycle. This problem could be minimized or perhaps eliminated by installing separate inlet and outlet lines from the oxygen storage tank. If all of the oxygen produced was allowed to mix in the tank, and was then withdrawn from a separate outlet, a more uniform percentage of gas would result. Although oxygen percentages above 99% would not normally be realized, neither would the lower values of 70% be seen. The resultant oxygen mixture would likely average no lower than 95%-97% purity. It should be noted that the cycling of oxygen percentage is a potential physiologic hazard only when the aircraft cabin altitude exceeds 25,000 ft (7,622 m) or the purity drops below 70%.

The second problem noted throughout the test program was the lower than specification oxygen production rate. The measured oxygen production rate was about 3.7 lb/hr (21 lpm at sea level, 21°C) which was about 20% below the minimum specification. The reduced oxygen production rate, together with the relatively small-volume (1-liter) storage tank, may compromise mission duration especially in high-demand situations. Static flow tests (Table 1) indicated a threefold reduction in oxygen duration time for a demand increase (ground level) of only 24% (60-min duration at 21 lpm demand, reduced to 20-min duration at 26 lpm demand).

It is recommended that the NAOGS storage pressure be monitored closely during the flight test program to guard against system depletion. Under stressful conditions, inflight minute ventilations for 2 crewmembers could be in the range from 40-50 lpm that, depending on altitude, may exceed the NAOGS capacity. The drain on oxygen storage will, of course, be greatest at ground level and decrease with altitude owing to gas expansion.

CONCLUSIONS

The NAOGS for the most part performed adequately during both manned and unmanned testing. The exceptions were the lower than specification oxygen production rate and the short-term drop in oxygen percentage during each sorbent bed cycle. The reduced oxygen production rate could create an oxygen deficiency problem if minute volume of aircrew were markedly increased by exercise or stress. However, this situation could be alleviated by installation of a larger oxygen storage tank, or possibly by adjustment of the temperature cycling time. Oxygen duration at altitudes above 18,000 ft (5,488 m) was satisfactory. Possible duration problems are foreseen, however, at lower altitudes and during startup, unless the oxygen production rate or storage capacity is increased.